Arrow of Time in Quantum and Cosmology: Energy Dissipation Entropy Driven by the Energy-Gradient Rule

Energy-Gradient Graph Automaton Model(EGG)

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Funding Declaration：No funding was received

Abstract

Building upon the analytic quantum thermodynamic framework I previously established (Zou, 2025), this article presents a discrete ontological model in which the arrow of time emerges from irreversible energy transfers driven by local energy gradients on a topologically fixed spatial network, with the temporal sequence identified as the successive updates of spatial energy redistribution. A multiplicative entropy, defined as the product of all node energies, increases exactly with every transfer, providing a non-statistical, step-by-step measure of temporal progression. I argue that energy dissipation is fundamentally identical to decoherence: the former supplies the physical mechanism, the latter the observational signature. This framework synthesizes three intellectual traditions—computational time (Wolfram, 't Hooft), gradient-driven thermodynamics (Annila), and decoherence (Joos & Zeh, Kiefer)—into a unified picture where time is the counting of irreversible energy redistribution on discrete space.

Zou, Z. K. (2026). Arrow of Time in Quantum and Cosmology: Energy Dissipation Driven by the Energy-Gradient Rule. Zenodo. https://doi.org/10.5281/zenodo.21212346
Previous Draft Updated from 2025 : https://doi.org/10.5281/zenodo.14788393

0. Introduction

This article builds upon the analytic quantum thermodynamic framework I previously established (Zou, 2025), which grounds time, entropy, and causality in a discrete elastic spacetime network of Space Elementary Quanta (SEQ). The arrow of time, in this view, emerges from irreversible energy redistribution driven by local energy gradients—a counting process of discrete state transitions that yields a computable, non-statistical multiplicative entropy.

This perspective aligns closely with the computational view of time advanced by Wolfram (2024) and 't Hooft (2018), who independently argue that time is not a fundamental coordinate but a sequential counting of elementary computational steps or state transformations in an underlying discrete substrate. It also converges with the gradient-driven evolution framework developed by Annila and collaborators (Tuisku et al., 2009; Annila, 2025), which identifies energy gradients as the universal driving force behind both quantum processes and cosmic evolution, with the Second Law manifesting as the natural tendency of energy to homogenize.

Crucially, the energy-dissipation arrow of time proposed here is not a rejection but a complementary interpretation of the decoherence-based arrow (Joos & Zeh, 1985; Kiefer et al., 2024, 2021). I argue that the process of energy dissipation is, at its core, identical to the process of decoherence. In the present ontology, decoherence and environment-induced superselection are understood as the macroscopic manifestations—observable through the lens of coarse-grained measurements—of the same underlying gradient-driven energy dissipation at the Planck scale. The two arrows are not competing mechanisms but two descriptions of the same process: one dynamical and microscopic (energy flow down gradients), the other informational and phenomenological (loss of phase coherence through environmental entanglement). The former provides the physical mechanism; the latter provides the operational signature.

Thus, this work synthesizes three intellectual traditions—computational time (Wolfram, 't Hooft), gradient-driven thermodynamics (Annila), and decoherence (Joos & Zeh, Kiefer)—into a unified ontological picture where the arrow of time is a direct, exact, and irreversible consequence of energy redistribution on a discrete spatial network, observed from complementary theoretical perspectives.

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1. The Problem of Time in Quantum Physics

In the standard formulation of quantum mechanics, time enters as a continuous, external parameter. The Schrödinger equation is deterministic and time-reversible: given the state at time t_0, the state at any future or past time is uniquely determined. No fundamental distinction exists between the forward and backward temporal directions. Yet our macroscopic experience is overwhelmingly asymmetric—we remember the past but not the future, we age, and energy distributions spontaneously homogenize. This conflict between microscopic reversibility and macroscopic irreversibility has been a central puzzle since Boltzmann's pioneering work on statistical entropy.

The conventional resolution appeals to statistical mechanics: entropy is a measure of the number of microscopic configurations corresponding to a given macroscopic state. The Second Law is understood as a probabilistic tendency rather than an absolute law: isolated systems evolve toward states of higher probability, but fluctuations that decrease entropy are not strictly forbidden. While this framework has been enormously successful, it suffers from several conceptual limitations. First, statistical entropy is inherently coarse-grained; it discards microscopic information and cannot track the detailed dynamical trajectory of a system. Second, the probabilistic interpretation of the Second Law leaves open the possibility of entropy-decreasing fluctuations, which have never been observed in closed macroscopic systems. Third, it provides no direct, mechanistic connection between entropy increase and the flow of time itself.

The Energy-Gradient Graph Automaton (EGG) model, as presented in the first three chapters of the foundational paper, offers an alternative ontology that addresses these limitations. By postulating a discrete, topologically fixed spatial network of energy-carrying nodes, and a local energy-transfer rule driven by energy gradients, the model constructs time and entropy from the ground up. The arrow of time is not an emergent approximation but an exact, step-by-step feature of the underlying dynamics.

2. The Ontological Substrate: Space Elementary Quanta (SEQ)

2.1 The Topologically Fixed Network

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The EGG model begins with a fundamental postulate: the universe consists of a finite number of Space Elementary Quanta (SEQ) arranged in a three-dimensional, topologically homeomorphic network. The adjacency relations between SEQ—which nodes are neighbors—are fixed and invariant throughout the entire evolution of the universe. This topological invariance is not an arbitrary assumption but is motivated by empirical and theoretical considerations.

From a phenomenological perspective, observations of light bending around massive objects such as black holes reveal smooth spatial curvature without evidence of topological tearing or discontinuities. The gravitational field remains well-defined, and the connectivity structure of spacetime appears stable even under extreme conditions. From a theoretical standpoint, the validity of the Feynman path integral method presupposes the existence of a well-defined measure on the space of paths. If the topology of space were to change dynamically—altering adjacency relations and the set of possible paths—the path integral would become ill-defined. Since the path integral has been extensively validated in quantum field theory, it is reasonable to infer that the underlying spacetime background operates within a stable topological class.

Thus, the EGG model posits that the connectivity graph of SEQ is fixed. All motion, change, and physical processes correspond to the redistribution of energy across this immutable network. This built-in topological invariance provides an intuitive physical picture for the constancy of the speed of light, offers a concrete mechanism for global energy conservation, and simplifies the mathematical formulation of the model.

2.2 The Two-Layer Structure: Sub-Planckian Substrate and SEQ

Each SEQ is not a primitive, point-like entity. Rather, it is a topologically stable structure formed from a deeper, sub-Planckian elastic substrate. The sub-Planckian layer consists of elastic components that mediate interactions between SEQ, much like springs connecting nodes in a mechanical network. The SEQ themselves emerge as stable excitations or "knots" within this elastic medium.

This two-layer structure is crucial for resolving a longstanding tension between general relativity and quantum field theory. In general relativity, spacetime is a smooth, continuous geometric manifold; in quantum field theory, matter fields are defined on a fiber bundle over spacetime, carrying spin and gauge degrees of freedom. The two formalisms appear incompatible because they rely on fundamentally different mathematical structures. However, within the EGG model, the sub-Planckian elastic

substrate provides a common foundation: the spin of SEQ arises from torsional elastic waves propagating on the substrate, while the elastic deformations of the network correspond to the geometric degrees of freedom of general relativity. Because spin and elasticity are fundamentally different types of excitations on the same substrate, they can coexist without interfering—especially in low-energy states. This decoupling mechanism allows the model to simultaneously support the metric field of general relativity and the gauge fields of quantum field theory.

2.3 Energy Quantization and Ground State

Each SEQ carries an integer amount of energy, denoted m_i, measured in units of Planck's constant h. Thus, the energy of the i-th SEQ is given by

$$E_i = m_i h ,$$

where $m_i \in \mathbb{N}$ (positive integers). The total energy of a closed system is conserved:

$$E_total = \Sigma_i m_i h = constant .$$

This quantization is not merely a mathematical convenience but reflects the fundamental discreteness of the model. Energy can only exist in integer multiples of h, and transfers occur only in discrete jumps of one quantum.

Crucially, the ground state of each SEQ carries at least one unit of energy: $m_i \geq 1$. This non-vanishing ground-state energy has significant implications. It provides a natural candidate for the cosmological constant in general relativity, and if the ground-state spin chirality of SEQ is fixed, it may explain the observed violation of parity in weak interactions. The fixed chirality also plays a central role in the model's interpretation of the Higgs mechanism and the scarcity of antimatter.

2.4 Elastic Bonds and Spacing Modulation

Adjacent SEQ are interconnected by elastic bonds—the sub-Planckian springs mentioned above. These bonds maintain a dynamic equilibrium spacing under normal conditions. The bonds can be compressed or stretched by energy redistributions, and these deformations store elastic potential energy. The elastic response of the network is nonlinear and asymmetric: compression and stretching have different elastic coefficients, reflecting the chiral nature of the substrate.

Importantly, the sub-Planckian elastic components impose an upper bound on the degree of spacing modulation and tension between adjacent SEQ. This fundamental limit ensures that extreme deformations—such as those near black hole

singularities—cannot tear the topological fabric of the network. Thus, the model naturally resolves the singularity problem of general relativity without invoking exotic physics.

The harmonic oscillation period of SEQ is an integer multiple of Planck time t_p. Consequently, all dynamical processes—including elastic strain interactions, harmonic conduction, and spinor field transmissions—are fundamentally constrained by discrete Planck-time intervals. This property ensures consistency with the discrete-time hypotheses in quantum gravity theories and provides a natural cut-off for ultraviolet divergences.

2.5 Isotropy and Lorentz Covariance

Any discrete model of spacetime must confront the challenge of restoring spatial isotropy so as to be compatible with the Lorentz-covariant rules established by observation. The EGG model addresses this in two ways. First, the topological network may contain primordial periodic or random dislocations that ensure physical isotropy. These defects are frozen in from the birth of the universe and preserve the overall 3D homeomorphism. Second, because the sub-Planckian constituents are far smaller than the Planck scale, their statistical distribution can be tuned so that, within observational precision, the resulting dispersion relation is effectively Lorentz-covariant. Thus, macroscopic isotropy emerges naturally and remains consistent with all current experimental data.

3. Energy Transfer Dynamics: The Gradient Rule

3.1 The Fundamental Driving Force

The dynamics of the EGG model are governed by a single, local rule: energy flows from higher-energy SEQ to adjacent lower-energy SEQ. Specifically, an energy transfer can occur between neighboring nodes i and j if and only if

$m_i > m_j + 1$.

When this condition is satisfied, one quantum of energy (Planck's constant h) is transferred:

$m_i \to m_i - 1$, $m_j \to m_j + 1$.

This gradient-driven update rule is the microscopic realization of the Second Law of Thermodynamics. It ensures that energy spontaneously flows downhill along the steepest available gradient, homogenizing the energy distribution over time. The rule is irreversible: once a transfer has occurred, the reverse transfer (from j back to i) is forbidden unless the energy gradient later reverses due to subsequent transfers involving other neighbors.

This local rule serves as the underlying mechanism for various gradient drives in traditional physics. Under appropriate approximation conditions, it reduces to:

- the potential energy gradient driving Newtonian mechanics,
- the temperature gradient driving thermodynamics,
- the metric curvature gradient driving general relativity,
- the electric potential gradient driving electrodynamics.

Thus, the EGG model provides a unified, bottom-up foundation for all known forces, rooted in the simple principle that energy seeks uniformity.

3.1.1 The Illusion of Reversibility: Why All Quantum Processes Are Irreversible

A potential objection to the gradient-driven dynamics is the apparent reversibility of quantum processes. Quantum optics experiments routinely demonstrate coherent superposition, quantum interference, and even time-reversal-like operations such as spin-echo or photon-echo. Do these not contradict the claim that all dynamics are fundamentally dissipative and gradient-driven?

The answer lies in carefully delineating the system boundary. In every experiment that exhibits coherent quantum behavior—whether it is a trapped ion, a superconducting qubit, a Bose–Einstein condensate, or an optical interferometer—the quantum system of interest is never truly closed. It is maintained in its low-entropy, coherent state by an elaborate external apparatus: lasers provide cooling and trapping; magnetic fields confine and manipulate; radio-frequency drives control spin states; cryogenic refrigerators remove heat; and precision vacuum systems isolate the system from environmental decoherence. Each of these external devices consumes energy and dissipates heat into the broader environment. When the entire closed system—quantum sample plus all supporting apparatus plus the surrounding thermal bath—is considered, the net evolution is overwhelmingly dissipative. Energy flows from high-gradient sources (electrical power, chemical batteries, laser pumps) into

low-gradient sinks (the laboratory environment, ultimately the cosmic microwave background). The apparent reversibility of the quantum subsystem is a temporary, locally sustained excursion sustained by a continuous influx of free energy. It is the thermodynamic equivalent of a carefully balanced pencil standing on its tip—stable only as long as external constraints are actively maintained, but thermodynamically unstable and ultimately irreversible when the full system is accounted for.

This perspective aligns with a fundamental fact: no empirical evidence supports the spontaneous reversible evolution of any closed physical system—whether classical, quantum, or cosmological—without external intervention. All observed dynamical processes, when their complete boundary conditions are properly accounted for, are thermodynamically irreversible. Electrons in atomic orbitals continuously radiate; the ground-state electron is an idealization, not a reality. Superconducting currents decay unless refrigerated. Quantum states decohere unless continuously corrected by error-correction protocols that themselves consume energy and generate entropy. There is no known phenomenon that supports a truly reversible, spontaneous return to a past state in a closed system.

Therefore, the unitary evolution postulate of quantum mechanics—the assumption that quantum states evolve reversibly under the Schrödinger equation—is not a fundamental law of nature but an approximation valid only for carefully isolated subsystems over short time scales. The genuine, foundational dynamics is the gradient-driven, entropy-increasing energy redistribution described by the EGG model. In this view, quantum coherence is not a violation of the Second Law but a metastable pattern sustained by external free-energy gradients—a special case of the general principle that energy flows from higher to lower concentrations, never the reverse, unless work is supplied from outside. And when that external work is included in the system boundary, the irreversibility is restored.

This argument is not merely philosophical; it is computationally concrete. In the EGG framework, any attempt to simulate a "reversible" quantum gate must include the energy cost of the controlling fields, the dissipation in the control electronics, and the heat dumped into the environment. When these are modeled as additional SEQ nodes with their own energy gradients, the net entropy of the total closed system increases with every operation. The apparent reversibility of the logical qubit is a local, transient phenomenon—a standing wave pattern in a river of entropy production.

3.1.2 The Identity of Energy Dissipation and Decoherence: Two Sides of the Same Process

The decoherence program, pioneered by Joos and Zeh (1985) and developed by Kiefer and collaborators (2024, 2021), has established that classical properties emerge from the irreversible loss of quantum phase coherence through interaction with the environment. This is an informational account: it describes how interference is

suppressed and how a preferred basis is selected, without explaining why this process is thermodynamically unavoidable.

The energy-dissipation perspective supplies exactly that missing explanation. When energy flows down local gradients from higher to lower concentrations, it redistributes itself irreversibly across the spatial network. This flow, at the microscopic level, is the physical process that generates entropy. The loss of quantum phase relations is not a separate phenomenon; it is the informational signature of that same energy redistribution. Every elementary energy exchange between a system and its environment is simultaneously a step of dissipation and a step of decoherence.

Thus, the two frameworks are not competing. Energy dissipation provides the physical mechanism: energy moves from higher to lower gradients, increasing entropy. Decoherence provides the observable consequence: phase relations decay, interference fades, and classical behavior emerges. One is the dynamical cause; the other is the measured effect. They describe the same underlying process from complementary perspectives — one thermodynamic, the other informational. In this view, the arrow of time is one, not two.

4. Multiplicative Entropy: A Non- Statistical Measure of Disorder

4.1 Definition and Mathematical Properties

The central innovation of the EGG model is its definition of entropy as the product of all node energies:

$S = \prod_i m_i$,

where the product runs over all N SEQ in the closed system. This multiplicative entropy has several remarkable properties:

Energy Conservation: The sum Σ_i m_i is fixed, ensuring the First Law of Thermodynamics.
Spontaneous Increase: For any allowed energy transfer from a higher- energy node a to a lower- energy node b (with a > b + 1), the entropy ratio is

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$S_2 / S_1 = (a - 1)(b + 1) / (a\ b)$
$= 1 + (a - b - 1) / (a\ b) > 1$.

Thus, every possible energy transfer strictly increases entropy. There is no exception, no fluctuation, no probabilistic loophole. The Second Law holds as an exact, deterministic theorem.

Entropy Ceiling: The maximum entropy is achieved when all m_i are as equal as possible—that is, when the energy distribution is uniform. Because the total energy and the number of nodes are fixed, the product is maximized when the values are balanced. This follows directly from the AM- GM inequality.

Logarithmic Relation: After taking the logarithm, the multiplicative entropy aligns with the conventional Boltzmann entropy:

$\ln S = \Sigma_i \ln m_i$.

For large numbers of nodes and high energies, this approximates the standard statistical entropy $\ln \Omega$, where Ω is the number of configurations. However, the multiplicative entropy is exact and non- statistical; it is defined for every microscopic state, not just macroscopic averages.

4.2 Numerical Example of Dynamics

To illustrate the dynamics, consider a closed system of four SEQ with initial energy distribution [3, 1, 5, 3], total energy 12. The entropy (multiplicative) is initially

$S = 3 \times 1 \times 5 \times 3 = 45$.

From this state, multiple transfer paths are possible, depending on which adjacent pairs satisfy the gradient condition and which are selected:

Path A: Transfer from node 3 (energy 5) to node 2 (energy 1) yields [3, 2, 4, 3], with entropy

$S_A = 3 \times 2 \times 4 \times 3 = 72$.

Path B: Transfer from node 3 to node 4 (energy 3) yields [3, 1, 4, 4], with entropy

$S_B = 3 \times 1 \times 4 \times 4 = 48$.

Both paths increase entropy, but Path A increases it more. The system then continues with further transfers:

From [3, 2, 4, 3], transferring from node 3 to node 2 yields [3, 3, 3, 3], with entropy

$S = 3 \times 3 \times 3 \times 3 = 81$.

From [3, 1, 4, 4], the maximum entropy path leads to [3, 2, 3, 4], with entropy

$S = 3 \times 2 \times 3 \times 4 = 72$.

Notably, the completely uniform state [3, 3, 3, 3] has maximum entropy S = 81, but it may not be reachable if the energy differences between adjacent nodes are not all greater than 1 at each step. In this example, the final state [3, 3, 3, 3] is reachable by a specific sequence of transfers, but the system cannot continue beyond it because no adjacent energy difference exceeds 1.

This simple example illustrates several key features of the model:

- Multiple evolutionary paths are possible from a given initial state.
- Entropy increases monotonically along every allowed path.
- The maximum entropy state is the uniform distribution, which acts as an attractor.
- The final equilibrium state may depend on the path taken, but entropy is maximized regardless.

4.3 Maximum Energy Gradient Rule

When a node has multiple lower-energy neighbors, the system exhibits a preference for transferring energy along the path that yields the greatest entropy increase. Consider a node i with energy A, adjacent to nodes j and k with energies B and C, where A > B > C. The local entropy before transfer is

$S = A \times B \times C$.

If energy transfers to j (the higher-energy neighbor):

$S' = (A - 1)(B + 1)C = (A - 1)(B\,C + C)$.

If energy transfers to k (the lower-energy neighbor):

$S'' = (A - 1)B(C + 1) = (A - 1)(B\,C + B)$.

Since B > C, we have $S'' > S'$. Thus, the path with the larger energy difference (i.e., the steeper gradient) produces a greater entropy increase. This local rule is consistent with the principle of maximum entropy production, a well-known heuristic in non-equilibrium thermodynamics.

However, the maximum energy gradient path is not necessarily unique. If two neighbors have equal energies (and both are sufficiently lower than A), there may be multiple paths with the same entropy increase. This degeneracy introduces a

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fundamental source of indeterminacy into the dynamics: the system must "choose" among equally viable paths. As we shall see, this indeterminacy is the origin of quantum probability within the EGG framework.

4.4 Comparison with Traditional Statistical Entropy

Traditional statistical entropy, $S = k_B \ln \Omega$, is a measure of the number of microscopic configurations Ω consistent with a given macroscopic description. It is inherently coarse-grained; it discards microscopic information and only tracks the volume of phase space accessible to a system. As a result, it cannot provide information about the detailed dynamical trajectory of a system. Entropy increase in statistical mechanics is a probabilistic tendency, not an absolute law. Fluctuations that decrease entropy are theoretically possible, though exponentially suppressed in large systems.

Multiplicative entropy, by contrast, is a property of the actual microscopic state. It changes with every single energy transfer, preserving the full history of the system's dynamics. There is no coarse-graining; the entropy is defined at the Planck scale and can be computed step-by-step in a simulation. The increase is exact and irreversible; there is no possibility of a fluctuation that decreases the product.

This distinction has profound implications. In the EGG model, the arrow of time is not an emergent statistical phenomenon but a fundamental feature of the dynamics. Time itself is defined as the sequence of energy redistributions; each transfer corresponds to a tick of the universal clock. The entropy increase is not a side effect but the very substance of temporal progression.

4.5 Analytic and Computational Tractability

The multiplicative entropy is particularly well-suited for computational implementation. Because all energies are integers (multiples of h), the product is also an integer. This avoids the floating-point precision issues that plague simulations of continuous entropy functions. Moreover, the entropy update rule is local and can be computed in parallel: when a transfer occurs, the global entropy can be updated by multiplying by the ratio $(a-1)(b+1)/(a\ b)$, without needing to recompute the entire product.

The model's mathematical simplicity also makes it analytically tractable. The proof of entropy increase is trivial, and the conditions for equilibrium are clear. This stands in

stark contrast to traditional statistical mechanics, where the derivation of the Second Law requires subtle assumptions about ergodicity, coarse-graining, and the initial conditions of the universe.

5. Time as a Counting Process

5.1 Global Time

Within the EGG framework, global time is not an external parameter but the counting of energy transfers across the entire universe. Each transfer is a discrete event, separated by one Planck time t_p. Thus, the total number of transfers T that have occurred since the beginning of the universe defines the cosmic time:

$t = T \times t_p$.

This definition has several important consequences:

- Discreteness: Time is not continuous but granular. The Planck time is the smallest meaningful temporal interval.
- Irreversibility: Because energy transfers are irreversible, time has a built-in arrow. There is no distinction between "time reversal" and "entropy decrease"; both are impossible by definition.
- Finiteness: Since the number of SEQ N and the total energy E are finite, the number of possible energy transfers is also finite. Therefore, the universe has a finite lifetime; it will eventually reach maximum entropy and cease to evolve.

5.2 Space-Time-Entropy Mapping

A key insight of the EGG model is the direct mapping between space transformations, entropy values, and moments of time. Each spatial transformation (energy transfer) corresponds to a unique entropy value. Conversely, each entropy value may correspond to multiple transformations (if different paths yield the same product).

This mapping can be visualized as follows:

Space Transformation → Entropy Value S → Possible Moment t .

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While the mapping from transformations to entropy is many-to-one, the reverse is not: for a given entropy value, there may be multiple possible moments (if different histories produce the same product). However, because the entropy is strictly increasing, the temporal order is unambiguous: if $S_2 > S_1$, then $t_2 > t_1$.

This Space-Time-Entropy mapping provides a concrete realization of the thermodynamic arrow of time within a discrete framework. It aligns with the ADM formalism of general relativity, where time is encoded in the evolution of spatial hypersurfaces, while embedding the Second Law directly into the dynamics.

5.3 Local Time and Time Dilation

While global time is defined by the total number of universe-wide transfers, local time is operationalized as the number of transfers occurring within a specific spatial region. A local clock measures the accumulated transformations in its own local SEQ network.

Within this framework, the time dilation effects of special and general relativity have distinct mechanisms:

- Special Relativity (uniform motion): Time dilation arises purely from observer-dependent counting differences. Because light signals take time to travel, a moving clock's ticks are counted differently by a stationary observer, even though the moving clock itself undergoes the same number of local transfers. No physical deformation of space occurs.
- General Relativity (gravity and acceleration): Time dilation arises from actual deformation of the SEQ network. Gravitational fields compress or stretch the local network, which modulates the resonance frequency of the SEQ. Lower frequency means fewer transfers per external tick, so time genuinely slows down in that region.

- This distinction between perceptual (SR) and physical (GR) time dilation is a unique feature of the EGG model, providing a concrete physical picture that goes beyond the purely mathematical formulations of relativity.

In this physical picture, the four-dimensional formalism of general relativity—with its abstract geometric time curvature—is rendered fully representable within the three-dimensional SEQ network. Each lattice point possesses a harmonic oscillation frequency, which defines the pace of its proper time. The spatial distribution of these frequencies constitutes the time curvature of GR. Since the frequency of a spatial oscillator is related to energy via E=hν, the frequency scalar field of the SEQ network simultaneously encodes both the time geometry of relativity and the energy distribution of the system. Thus, gravitational time dilation is understood as the

modulation of local oscillator frequencies by network deformation, and gravitational redshift follows directly from frequency gradients between spatial points. In this way, the abstract 4D Riemannian time geometry is mapped onto an intuitive 3D geometry equipped with a scalar frequency field—a mapping that makes the connection between time curvature and energy distribution explicit, and provides a concrete physical realization of the temporal component of general relativity in terms of local oscillator dynamics on a discrete spatial network.

5.4 The Physical Meaning of Planck Time

In this framework, the Planck time t_p corresponds to the fundamental minimum harmonic period of the SEQ network in its equilibrium state—the duration of a complete energy transfer (or harmonic oscillation period) between adjacent SEQ. This period defines the theoretical maximum transformation frequency of the universe.

While gravitational fields can locally modulate the harmonic frequency by deforming the SEQ network (as in gravitational time dilation), the global maximum transformation frequency remains anchored by t_p in the equilibrium state. However, due to the omnipresence of gravitational effects, the empirically observable maximum transformation frequency of space is slightly less than this theoretical limit.

6. Causality and the Principle of Least Action

6.1 Causality as Constrained Evolution

Within the EGG model, causality is determined by three fundamental principles:

- The Second Law (Entropy Increase): Energy always flows from higher to lower nodes, ensuring irreversibility.
- The Maximum Entropy Path Principle: When multiple transfers are possible, the system favors the path that produces the greatest entropy increase.
- The Principle of Least Action: The system tends to follow paths that minimize the total number of energy transfers required to reach a given final state.

- At the microscopic scale, the evolution is Markovian: each state transition depends only on the current energy distribution. However, the possibility of multiple maximum- entropy paths introduces genuine indeterminacy. The principle of least

action, as a global constraint, further reduces the number of viable paths but does not necessarily select a unique one. Thus, the future retains degrees of freedom even under the full set of dynamical rules.

6.2 Action as Counting

In the EGG model, action is reinterpreted as the total number of energy transfers:

$S_action = \Sigma_i \, h \, k_i$,

where k_i is the number of transfers involving the i-th SEQ, and h is Planck's constant. The principle of least action then corresponds to minimizing the total number of transfers.

This counting interpretation has a clear physical meaning: nature selects paths that require the fewest quantized energy jumps. When spacetime is curved, stretched regions have lower SEQ density, requiring fewer quanta for propagation. Thus, light bending around a massive object is simply the path of minimal transfers through the deformed network.

6.3 Conjecture: Maximum Entropy Path = Least Action Path

The model proposes a conjecture that, under the global maximum entropy path condition (i.e., following the path that maximizes entropy at every step from the initial to the final equilibrium state), the number of transfers is minimized. If true, this would establish an equivalence between maximum entropy production and least action, unifying thermodynamics and variational mechanics.

However, this conjecture remains unproven. The local maximum energy gradient rule does not guarantee global optimality; multiple paths with the same local entropy increase may lead to different total transfer counts. For this reason, the global maximum entropy path appears to require a supra-Markovian selection rule that incorporates information about the future state—a feature reminiscent of superdeterminism in computational models.

7. Quantum Indeterminacy and the Origin of Probability

7.1 Randomness as Path Degeneracy

In the EGG model, quantum randomness is not an intrinsic feature of nature but a reflection of the non-uniqueness of future paths. When multiple transfers satisfy the gradient condition and yield the same entropy increase, the system has genuine freedom. The Schrödinger equation's probabilistic interpretation arises because the system explores these multiple near-optimal paths in parallel at the Planck time scale, and the statistical weight of each path determines the probability amplitude.

Thus, the squared modulus of the wavefunction $|\psi|^2$ corresponds to the distribution of path weights in the ensemble of possible evolutions. This aligns with the path integral formulation of quantum mechanics, where the probability amplitude is a sum over all paths connecting initial and final states.

7.2 Complementarity and Entanglement

The model provides a simple explanation for the uncertainty principle: knowing a particle's exact position requires localizing it to a single SEQ, which loses information about its wave-like propagation across the network. Similarly, wave-particle duality emerges naturally: the wave nature is fundamental, while the particle nature arises from the discreteness of the network.

The model's treatment of entanglement is also noteworthy. In the EGG framework, the global constraint of energy conservation, combined with symmetric configurations of the energy distribution, can produce correlations between spatially separated nodes without any non-local interaction. For example, if two nodes are symmetrically positioned relative to a central region, their energy states may become correlated because any transfer that breaks the symmetry would require a specific, unlikely sequence. Thus, entanglement is reinterpreted as a consequence of global conservation laws and the topological structure of the network, rather than a violation of local causality.

7.3 The Markovian Constraint and Future Indeterminacy

Although the evolution is Markovian—each step depends only on the current state—the existence of multiple maximum-entropy paths means that the future is not uniquely determined. This is the source of genuine indeterminacy in the quantum domain. However, because the Markov property ensures that the future depends only on the present, no hidden variables or non-local influences are required. The apparent

randomness of quantum measurements is simply a reflection of the system's freedom to choose among equally valid thermodynamic paths.

This perspective has profound implications for the interpretation of quantum mechanics. It suggests that the unitarity postulate—the assumption that quantum evolution is reversible—may be only an approximation, valid in regimes where entropy production is negligible. In the full Planck-scale dynamics, irreversibility is fundamental, and the Schrödinger equation is a coarse-grained description of a deeper, dissipative process.

8. Conclusion: The Ontological Arrow of Time

The Energy-Gradient Graph Automaton model provides a self-consistent, bottom-up framework in which the arrow of time is an exact, irreversible feature of microscopic dynamics. By grounding entropy in a multiplicative product of discrete energies, the model establishes a non-statistical, step-by-step measure of temporal progression. The Second Law of Thermodynamics holds as a theorem, not a probabilistic tendency. Global time emerges as the counting of energy transfers, while local time dilation arises from modulation of the transfer rate due to spatial deformation.

This framework offers several conceptual advances:

- Unification of Time and Entropy: Time is not an external parameter but the sequence of entropy-increasing steps. The passage of time and the increase of entropy are the same phenomenon, viewed from different angles.
- Resolution of the Reversibility Paradox: There is no conflict between microscopic dynamics and macroscopic irreversibility because the dynamics are fundamentally irreversible at the Planck scale. The apparent reversibility of quantum mechanics is a coarse-grained approximation.
- Origin of Quantum Probability: Randomness arises from the non-uniqueness of maximum-entropy paths, not from intrinsic indeterminism. The Schrödinger equation's probabilities reflect the statistical distribution of these paths.
- Bridge Between General Relativity and Quantum Field Theory: The two-layer substrate allows spin and elasticity to coexist, enabling the metric field of GR and the gauge fields of QFT to be unified in a single ontological framework.
- Computational Tractability: The model is designed for numerical simulation, with integer energies, local update rules, and exact entropy increase. This makes it well-suited for exploring the emergence of classical behavior from discrete quantum dynamics.

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Previous Draft Updated from 2025 : https://doi.org/10.5281/zenodo.14788393

- The EGG model is not merely a philosophical speculation but a concrete proposal for a computable universe. Its postulates are simple, its consequences are rich, and its predictions—such as a measurable difference between the magnetic moments of the positron and the electron—are experimentally falsifiable. While much work remains to formalize the model's mathematical structure and derive its full empirical content, it offers a promising new direction for understanding the nature of time, entropy, and quantum reality.

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